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MEMORANDUM REPORT NO. 1843

DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS AT THE BRL SHOCK TUBE FACILITY

by

George A. Coulter

May 1967

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George A. Coulter

Terminal Ballistics Laboratory

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ABERDEEN PROVING GROUND, MARYLAND

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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

MEMORANDUM REPORT NO. 1843

GACoulter/sjw
Aberdeen Proving Ground, Md.
May 1967

DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS AT
THE BRL SHOCK TUBE FACILITY

ABSTRACT

Dynamic pulse calibration methods and types of pulse calibrators currently in use at the Ballistic Research Laboratories (BRL) Shock Tube Facility are described. Records typical of the various calibration methods obtained from piezo-electric tourmaline transducers are shown. Results from the various calibration methods are found to be in agreement with each other within ± 1.5 percent.

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I. INTRODUCTION

A dynamic pressure calibration is a very necessary and desirable part of any testing procedure for newly designed transducers. Also, a dynamic calibration is needed for the selection of blast wave transducers intended for use in large scale field tests. The transducer's natural frequency, rise time, possible deviations from static calibration, and other such characteristics may be observed during the dynamic calibration of the transducer. In particular, some piezo-electric transducers cannot be statically calibrated because of their lack of low frequency response; a dynamic pulse calibration is, therefore, very necessary for such a transducer.

The purpose of this report is to present the methods of dynamic calibration of pressure transducers currently in use at the Ballistic Research Laboratories (BRL) Shock Tube Facility. Typical calibration results are shown as pressure-time traces obtained from tourmaline crystal pressure transducers.[1*] These transducers have been described in Reference 1 in some detail so they will not be described here. A table listing the transducers and their characteristics is given in the Appendix of this report for ready reference.

The results of the calibrations will be presented according to type of calibration: (1) air pulse, (2) shock wave, and (3) a pulse from a dropped weight. A brief description of changes in gage output caused by both ambient and transient temperature changes is included.

II. CALIBRATION BY AIR PULSE

Air Pulse Calibration can be either portable or of the fixed panel type.

**Superscript numbers denote references which may be found on page 45.*

A. Portable Calibrator

For air pulse calibration at remote locations of pressure transducers, several portable calibrators are currently in use at the Shock Tube Facility. Basically the calibrator consists of air reservoir tanks, an electric solenoid valve modified to accept the transducer case, and a dial manometer to monitor the reservoir pressure.

Figure 1-A shows a photograph of one of these portable air pulse calibrators, and a typical record is shown in Figure 1-B. A three-way 230 psig Ansco solenoid valve, catalog No. x831428, is used which has a 3/64-inch orifice. A larger (3/32-inch) orifice caused oscillations initially on the pressure pulse; these made accurate reading difficult.

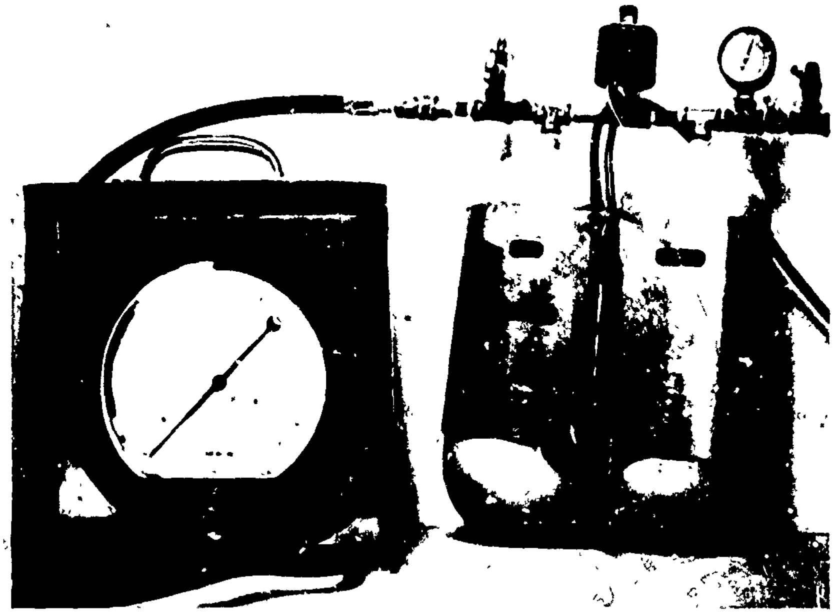
A reference charge is applied to the oscillograph (first pulse in Figure 1-B) in order to calculate an absolute charge output for the transducer. The charge and voltage reference unit used is described later in Section IV. The calibration procedure used was to sweep the oscilloscope, apply first the charge pulse, and then open the electric solenoid valve for the pressure pulse. If the air reservoir tank volume is very large (20,000:1) compared to the interior volume of the solenoid valve, the dial manometer may be read and assumed to give the magnitude of the pressure pulse applied to the transducer.

A simple comparison of the pulse heights of the reference charge and pressure pulse allows one to calculate the charge output per unit applied pressure. Three to five calibrations will establish a calibration accuracy error of less than 2 percent.[2]

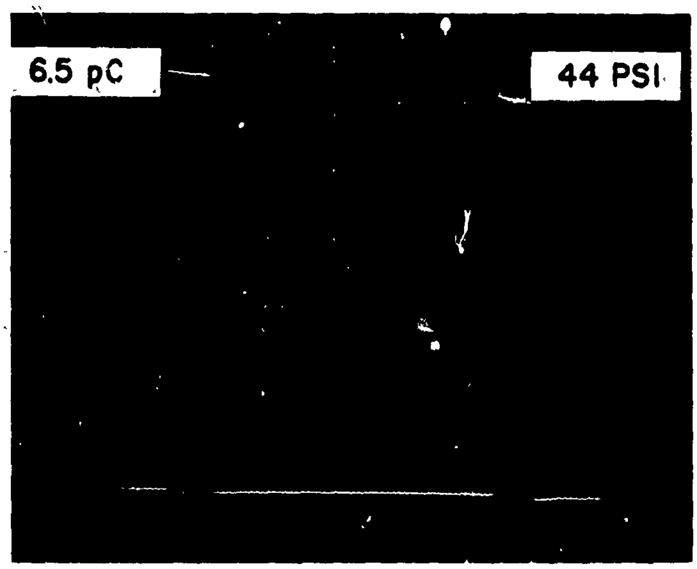
B. Intermediate Range Pressure Calibrator

For transducer calibration in the pressure range above 100 psig, a fixed panel calibrator is used. The upper pressure range is limited to about 2000 psig by the standard compressed nitrogen bottle now used. Special bottles can be obtained if one desires to reach perhaps 6000 psig.

Figure 2-A is a photograph of the calibrator shown with one of the recording systems in use. These consist of the transducer mounted in the calibrator head, the charge and voltage reference unit, a Kistler 566

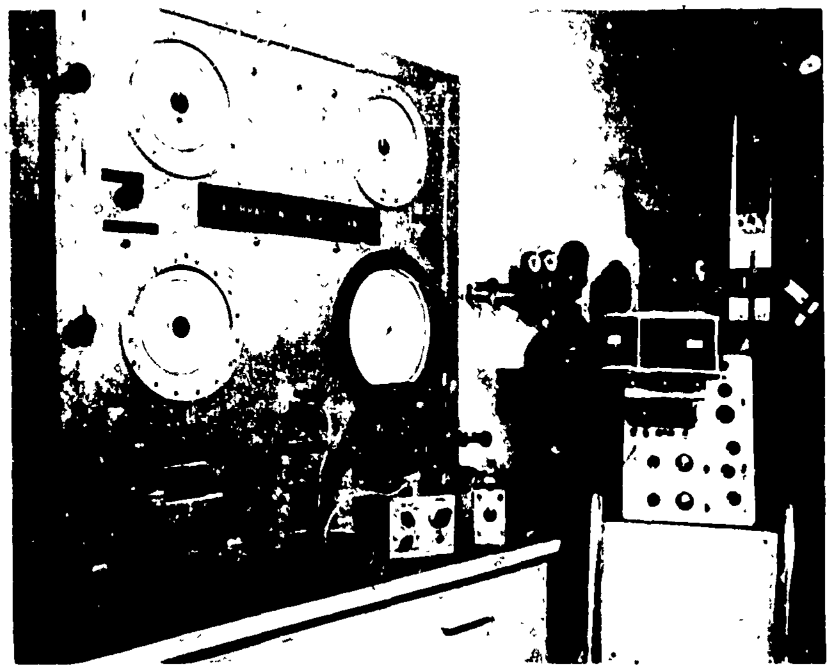


(A) PORTABLE CALIBRATOR

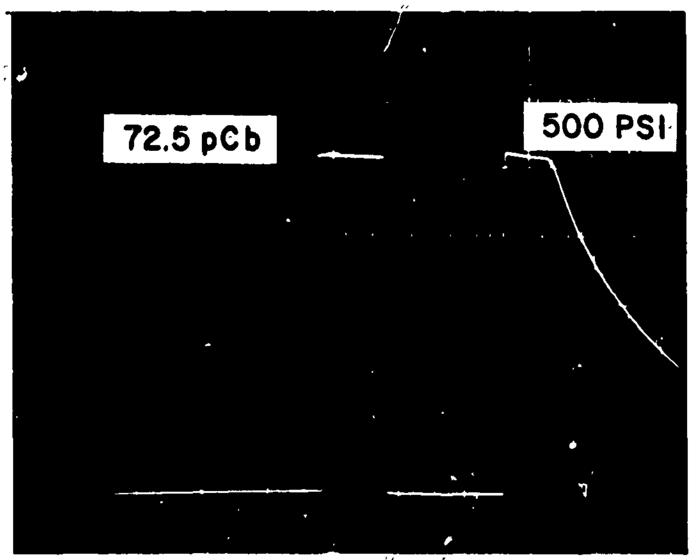


(B) CALIBRATION RECORD

Figure 1. Portable air pulse calibrator



(A) PANEL CALIBRATOR



(B) CALIBRAT ON REC ORD

Figure 2. Intermediate range panel calibrator

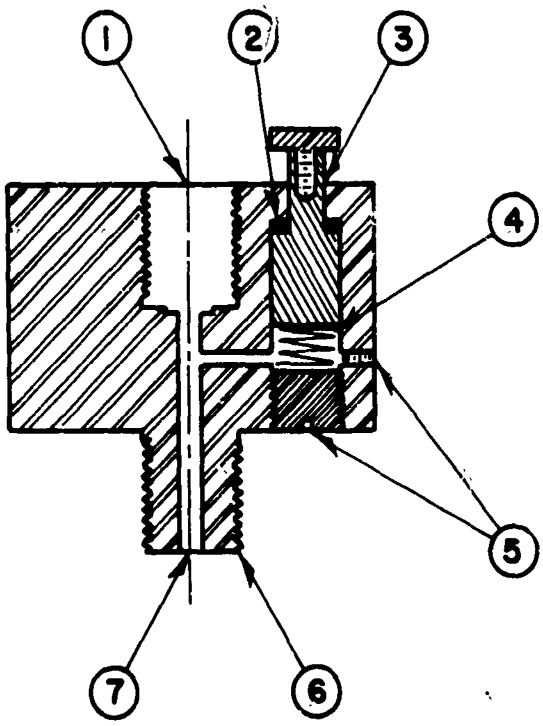
charge amplifier, and a Tektronix 502 oscilloscope. Representative calibration records shown in Figure 2-B are similar to those obtained from the portable calibrator with the exception that the pressure pulse decays slower at the end because the valve is two-way and does not immediately release the air as the three-way valve does. The calibration of charge output is made in the same manner as for output from the portable calibrator. A series of panel mounted dial manometer gages provides accurate pressure measurements over the entire range of calibration pressures.

Since commercial three-way solenoid valves that will operate at pressures to 2000 psig, are not ordinarily available, standard two-way valve was adapted as in Figure 3. A manual release valve was added to exhaust the pressure from the main valve volume after each calibration pulse. A TEFLON O-ring seal was substituted after a standard rubber O-ring did not release properly. The remaining parts seem not to be critical so long as the interior volume of the adapter remains small (1:20,000) compared to the reservoir volume. The exterior adapter body dimensions may be changed to suit inidvidual space requirements.

III. CALIBRATION BY SHOCK TUBE

The air-pulse calibrations described are both simple and quite accurate, but are somewhat limited by the risetime of about a millisecond caused by the orifices of the particular valves used. This is a disadvantage in that a transducer may function during a slow-rise air-pulse calibration but may have a different output or fail during the air shock loading. The transducer, when shock loaded, may be stimulated to vibrate, or ring at its natural frequency, and may break. To check this possibility, the somewhat more difficult shock tube calibrations are also used as a part of the transducer test program.

There are presently several shock tubes[3] available at BRL for this testing. Three such shock tubes will be described here: (1) the 24-inch shock tube, (2) a 2-inch calibration shock tube, and (3) the 2-inch



① TRANSDUCER PORT – 1/2-20 NF

② TEFLON O-RING

③ RELEASE VALVE

④ SPRING

⑤ PLUGS

⑥ 1/4 – 18 PIPE THREAD

⑦ AIR INLET FROM TWO-WAY SOLENOID VALVE

Figure 3. Adapter valve for two-way solenoid

propellant driver shock tube. The 2-inch calibration shock tube will be described in some detail, but the other tubes will be mentioned only briefly. Only needed working equations from the theory of shock tubes will be presented since an excellent review of shock tubes is available to the reader in Reference 4.

A. 24-Inch Shock Tube

The 24-inch shock tube is a constant area, cold gas driver type with a shock pressure range from less than 1 psig to 30 psig when air is used as a driver. The shock wave is started down the tube when a restraining diaphragm at the driver section is broken by a plunger. When the shock wave arrives at the test section (Figure 4), two piezo-electric trigger pickups start and stop a counter. An average velocity of the shock front is calculated from the measured time interval, and the known distance between the two pickups. Shock front pressure, P_s, is related to the velocity U by Equation 1:

$$P_s = \frac{7}{6} P_1 \left(\frac{U^2}{a_1^2} - 1 \right) , \tag{1}$$

where P_1 is ambient pressure (1 atmosphere in these calibrations) and a_1 is the ambient sound velocity. a_1 may be calulated from the ambient temperature, T_1, and is given for air by:

$$a_1 = 1088 \left(1 + \frac{T_1}{273} \right)^{1/2} \tag{2}$$

where T_1 is measured in degrees Centigrade.

When the shock tube is used for calibration, the transducer undergoing testing is installed flush with the inside wall of the test section and exposed to the desired shock overpressure. The output from the transducer may be monitored by a peak indicator such as the Kistler 593 indicator, or recorded as a pressure-time trace on an oscilloscope. The repeatability of two such shock tube shots are shown in Figure 5 for the BRL-3 tourmaline crystal transducer. (See Table A-I of the Appendix for

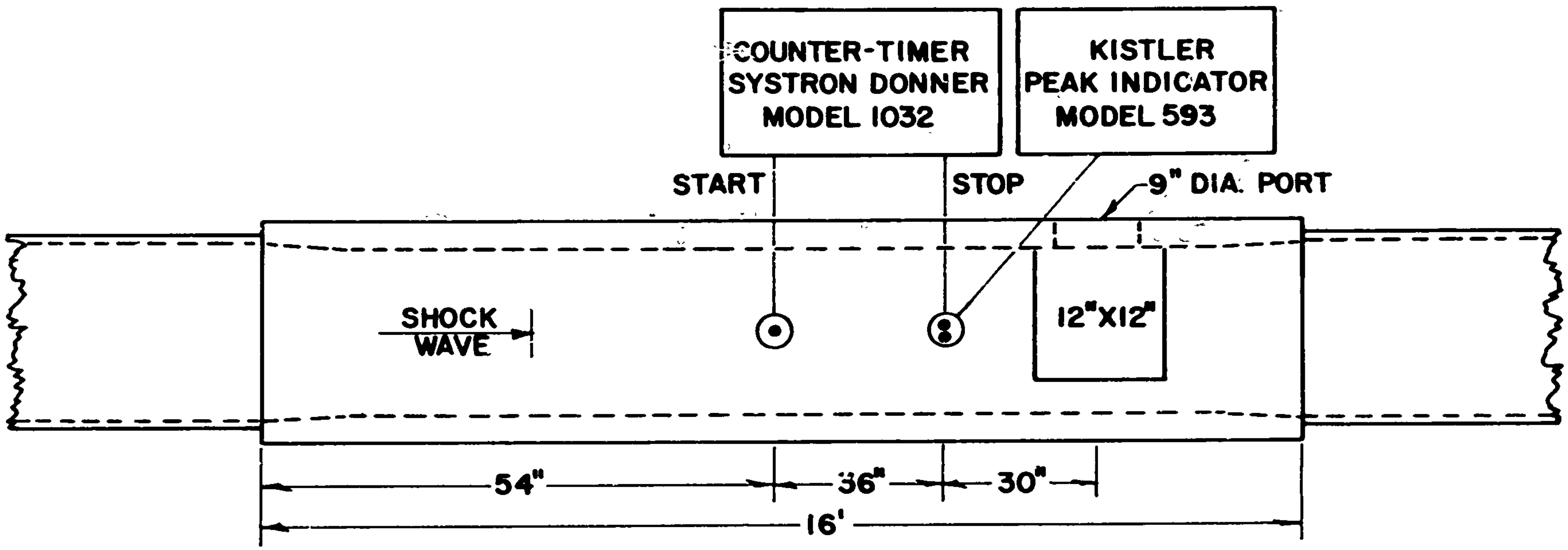
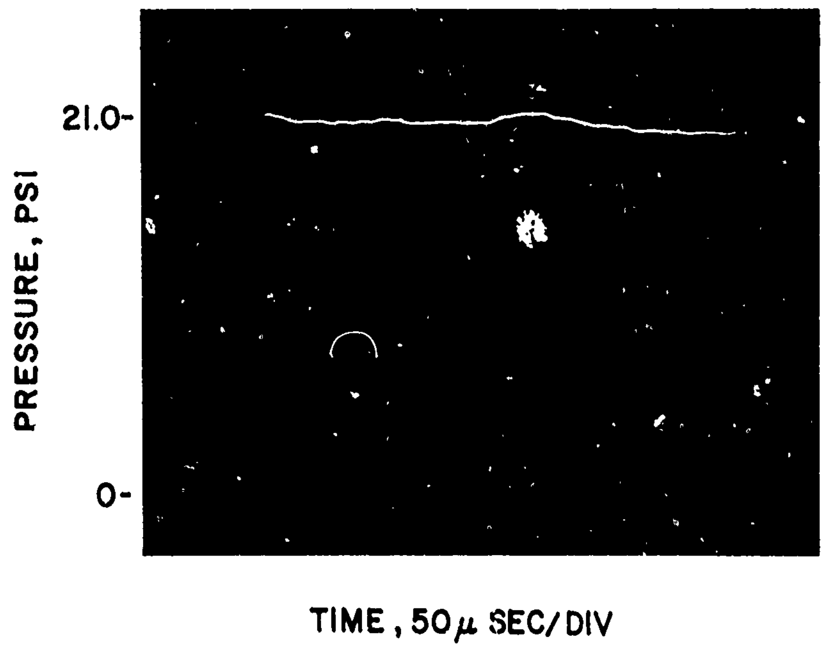


Figure 4. 20 x 20-Inch test section of the 24-inch shock tube



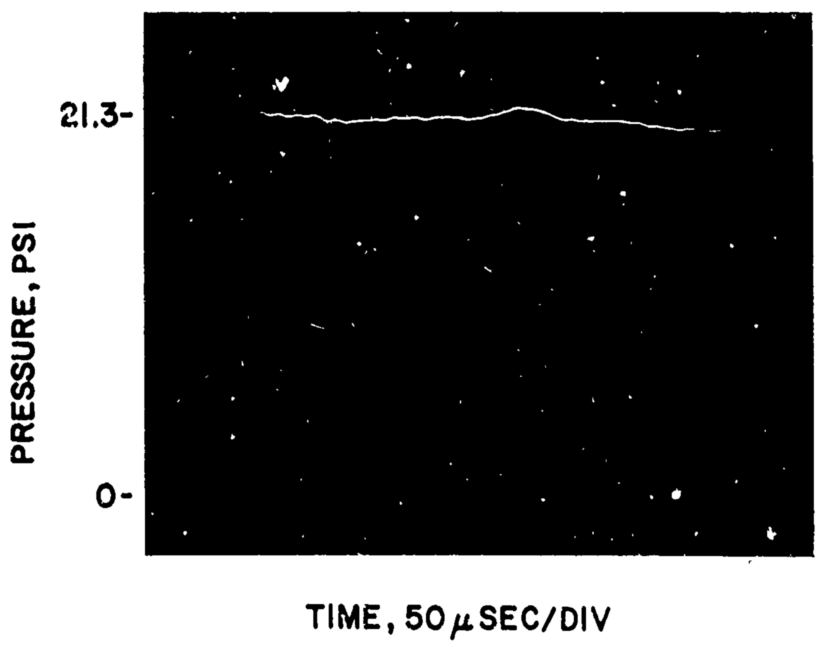


Figure 5. Typical pressure-time records from 24-inch shock tube

a current list of pressure transducers in use at the Shock Tube Facility.) Unwanted vibration noise has been removed by an electrical filter shown in Figure 6. Again, as in the air-pulse calibrations, the charge output per unit applied shock pressure may be calculated by using a known reference charge (not shown) and the value of the shock front pressure as calculated from the velocity system. The pulse risetime for the applied shockwave is limited by the crossing time over the sensitive element of the test transducer.

If calibration at a still faster risetime is desired, the pressure transducer may be mounted in a face-on position in the closed-end plate of the test section. In this position, the shockwave will hit the transducer normal, with a reflected pressure rise of less than a microsecond. To use the reflected pressure for a calibration, Equation (3) is used:

$$P_{ref} = 2\, P_s \left(\frac{7P_1 + 4P_s}{7P_1 + P_s} \right) , \tag{3}$$

where P_{ref} is the reflected overpressure corresponding to the calculated side-on shock pressure, P_s, for an ambient pressure, P_1. Equations (1) and (3) are for an assumed ideal air. Corrections for air as an imperfect gas may be made by using information from References 5 - 8 if more accurate calibrations are desired at the higher overpressures.

Usually reflected pressure calibrations are not made in the 24-inch shock tube, but are more easily accomplished in the smaller calibration shock tube described next.

B. 2-Inch Calibration Shock Tube

The 2-inch calibration shock tube is a smaller and much simpler copy of the 24-inch shock tube. The 2-inch tube also operates from a cold gas driver and is of constant area throughout. Instead of air, compressed bottled helium or nitrogen are used as driver gases; these cause pre-selected diaphragms to break and create the shock waves. Close

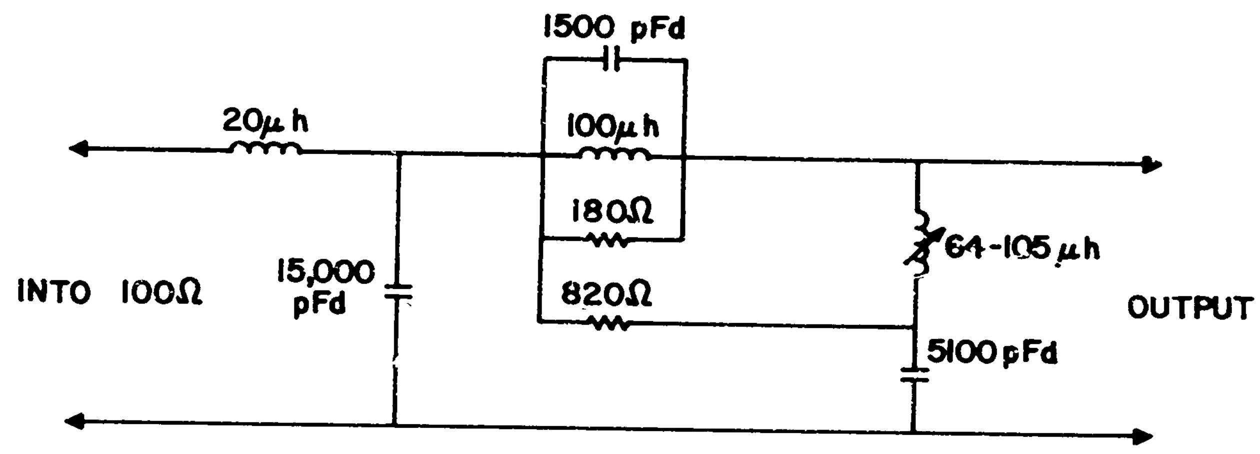


Figure 6. 250 Kc filter for the BRL-2 transducer

repeatibility of shock pressure is obtained without any scoring of the diaphragms. Figures 7 and 8 show the 2-inch calibration shock tube and the velocity system.

A short 6-inch baseline between counter trigger pickups is used to minimize any shock front attenuation that may occur. In order to adjust the counter triggers for equal risetime and amplitude, considerable care must be used; otherwise, a velocity error will cause an incorrect value for the calibration shock pressure.

BRL-2 piezo-electric transducers are currently used for the triggers in the calibration shock tube. The following procedure is followed when setting up the trigger levels on the counter, and may be used for other types of triggers as well. The method is as follows:

1. Calculate the trigger voltage from the pickup in the instrument to be triggered (the counter) from Equation (4),

$$V = \frac{QP}{C_c + C_g + C_{in} + C_b} \qquad (4)$$

Here V is trigger voltage, Q is the charge output in pC/psi (obtained from the air pulse calibrations), C_c is cable capacitance in pF, C_g is transducer capacitance, C_{in} is input capacitance to counter, C_b is ballast capacitance, if any, and P is equal to one-half the expected calibration shock overpressure, Ps, in psi.

2. Connect charge and voltage reference unit to counter start and stop inputs and adjust trigger voltage level to V calculated from Step 1 above. The voltage reference used is described later in Section IV.

The 2-inch calibration has test ports both side-on in the test section and face-on in the closed-end flange for a reflected pressure calibration. The peak-pressure instrument is omitted from the 2-inch tube, but the velocity system is used as in the 24-inch shock tube.

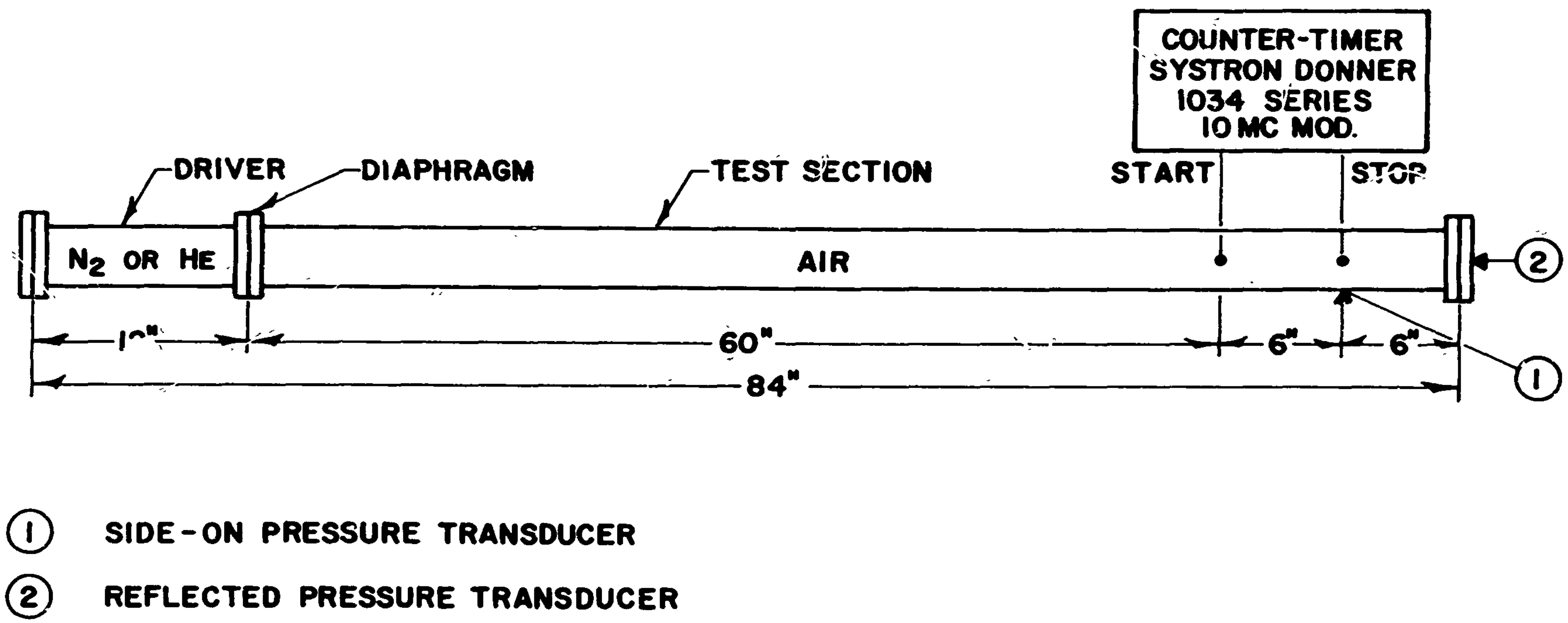


Figure 7. 2-Inch calibration shock tube

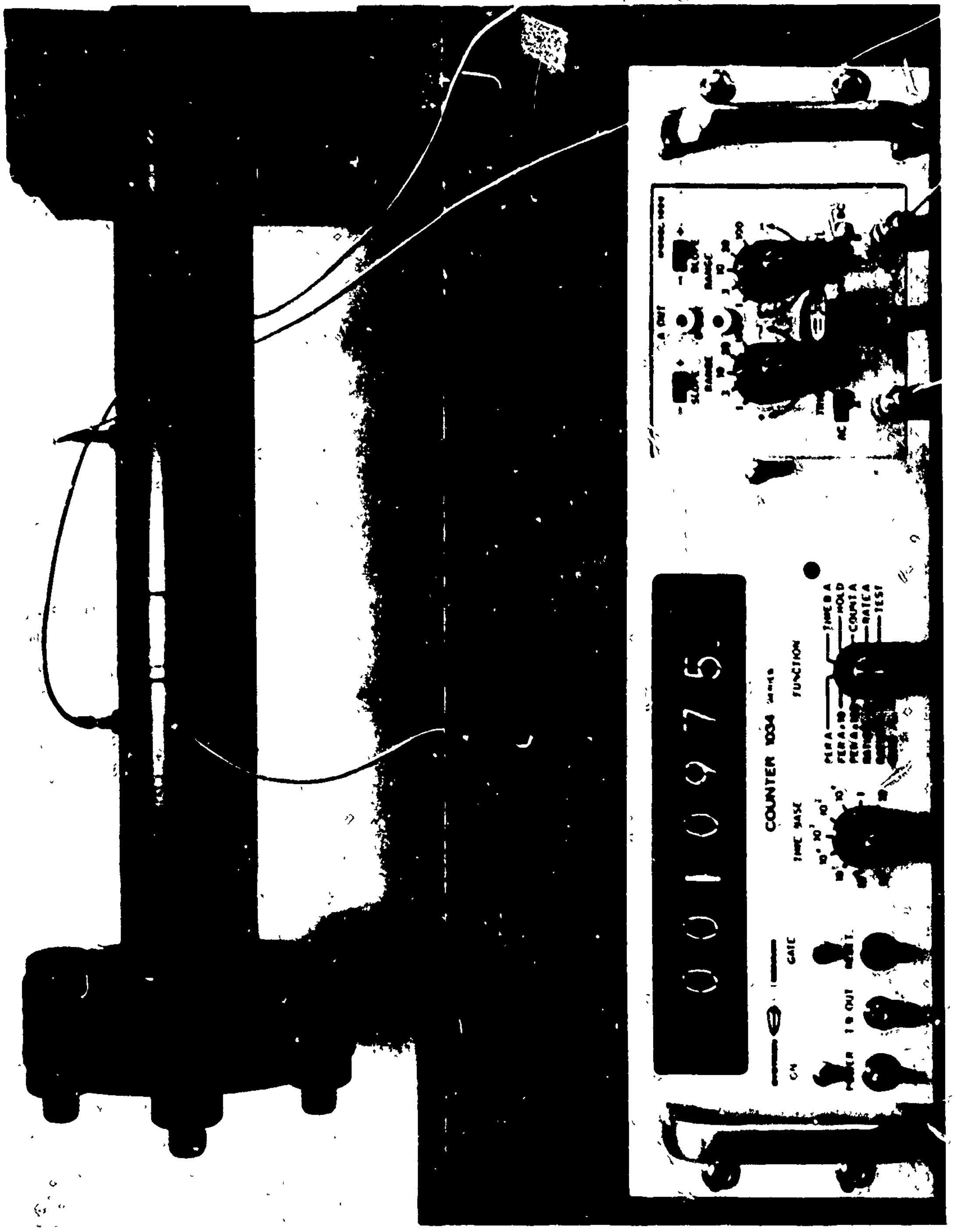


Figure 8. Test section of 2-inch shock tube

Tables I and II list shock tube specifications and expected pressures for several diaphragm-driver gas combinations. A side-on shock overpressure range between 32 and 180 psi is covered in the table. Intermediate values of pressure may be obtained by combining two or more diaphragms. All values of pressure are for slow filling to the driver. A change in the fill-rate or a substitute diaphragm of different hardness will change the expected pressure. To maintain the expected values, it is also necessary to evacuate the helium driver gas (if used) from the entire test section. The use of a vacuum cleaner for a period of a minute or so does an adequate job.

The pressure-time histories of the shock waves for some typical shots are shown in Figures 9 and 10. There occurs some vibration of larger amplitude than that seen in the traces from the 24-inch tube. These vibrations make the trace harder to read, but this difficulty is offset by the ease of operation and the greater range of calibration pressures available with the smaller tube.

C. <u>2-Inch Propellant Driver Shock Tube</u>

The ranges of calibration pressure are extended still higher than is possible in the 2-inch calibration tube by the use of M-9 propellant to drive a shock tube.[9] A gun with a 2-inch bore was altered to withstand the high pressure shock wave caused by burning propellant. This wave is contained by a diaphragm separating the driver and test sections. As in the calibration shock tube, a diaphragm is chosen to break with the desired driver pressure. A sketch of the shock tube and typical traces from the transducers are shown in Figures 11 and 12. Again, the records show increased vibration as the shock pressure is increased.

The test environment in the propellant shock tube is one of very harsh temperature and pressure, but these conditions give a more realistic evaluation of transducers intended for field use where they are to measure blast waves from large scale explosions.

Table I. Specification for 2-Inch Calibration Shock Tube

Material	Length of Shock Tube	Driver Gas	Diaphragm Material	Instrumentation
Seamless, round, cold drawn mechanical steel tubing - 3-inch ODx1/2-inch wall thickness.	Driver - 1 foot	Helium or Nitrogen	11 - 00 - 0 Aluminum or Mylar	Interval Counter for velocity calculations.
Slip-on forged steel flanges 2 1/2-inch pipe size, 7-inch OD, 150 lb. Sections bolted with 3/4-inch x 3-inch long bolts.	Test Section- 6 feet			

Table II. Shock Pressure as a Function of Diaphragm Type and Driver Pressure - 2-Inch Shock Tube

Shock Overpressure, psi	Reflected Overpressure, psi	Diaphragm Material	Driver Gas	Driver Pressure, psig
		11 - 00 - 0 Aluminum		
180	1050	0.064 inch	Helium	1400
144	790	0.040		880
130	690	0.032		760
90	435	0.020		423
58	245	0.032	Nitrogen	760
		Mylar		
32	110	0.010 inch	Nitrogen	225

NOTE: Fill driver slowly to obtain pressures listed.

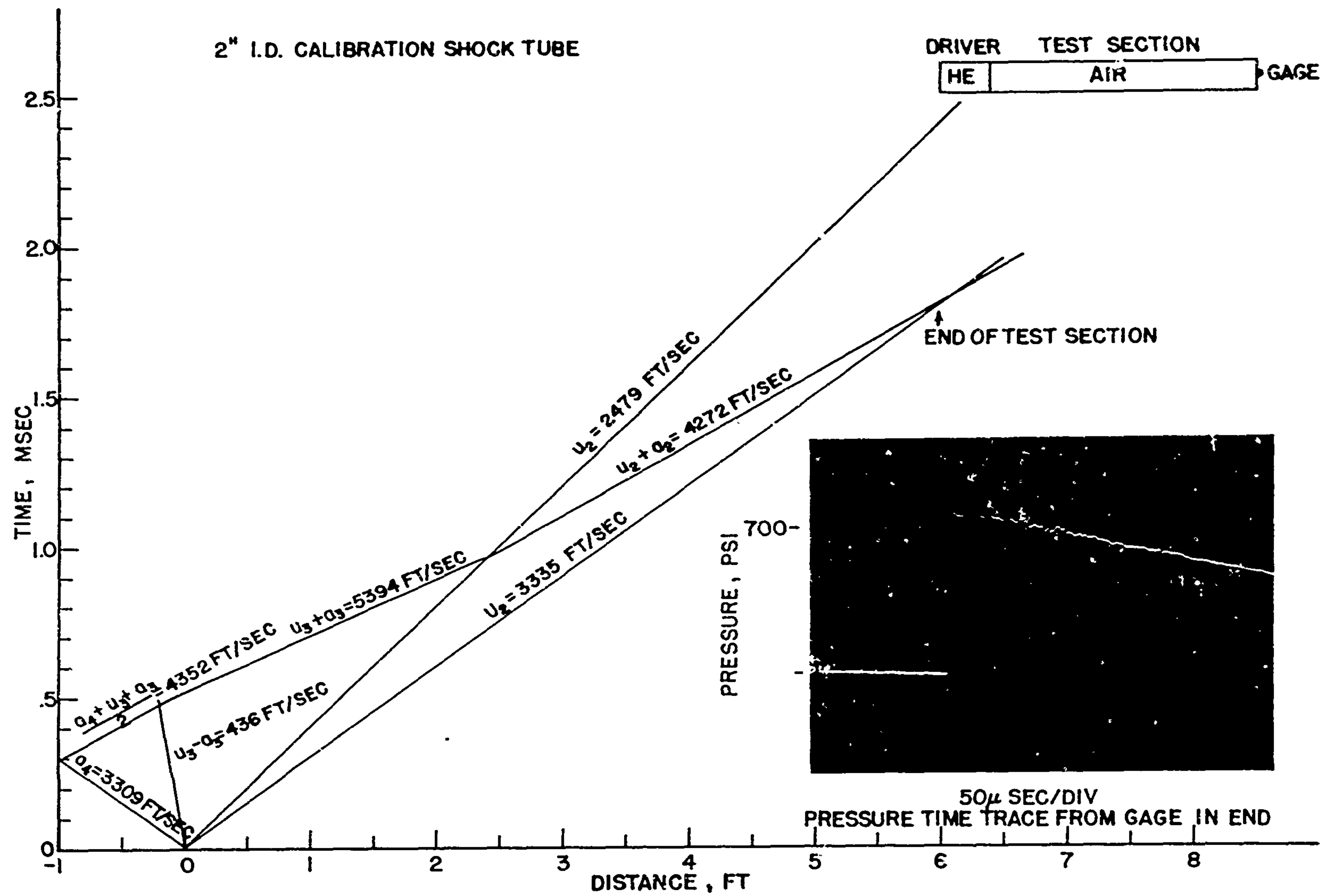


Figure 9. Wave diagram for helium-air calibration shock tube - P_s = 134 psi

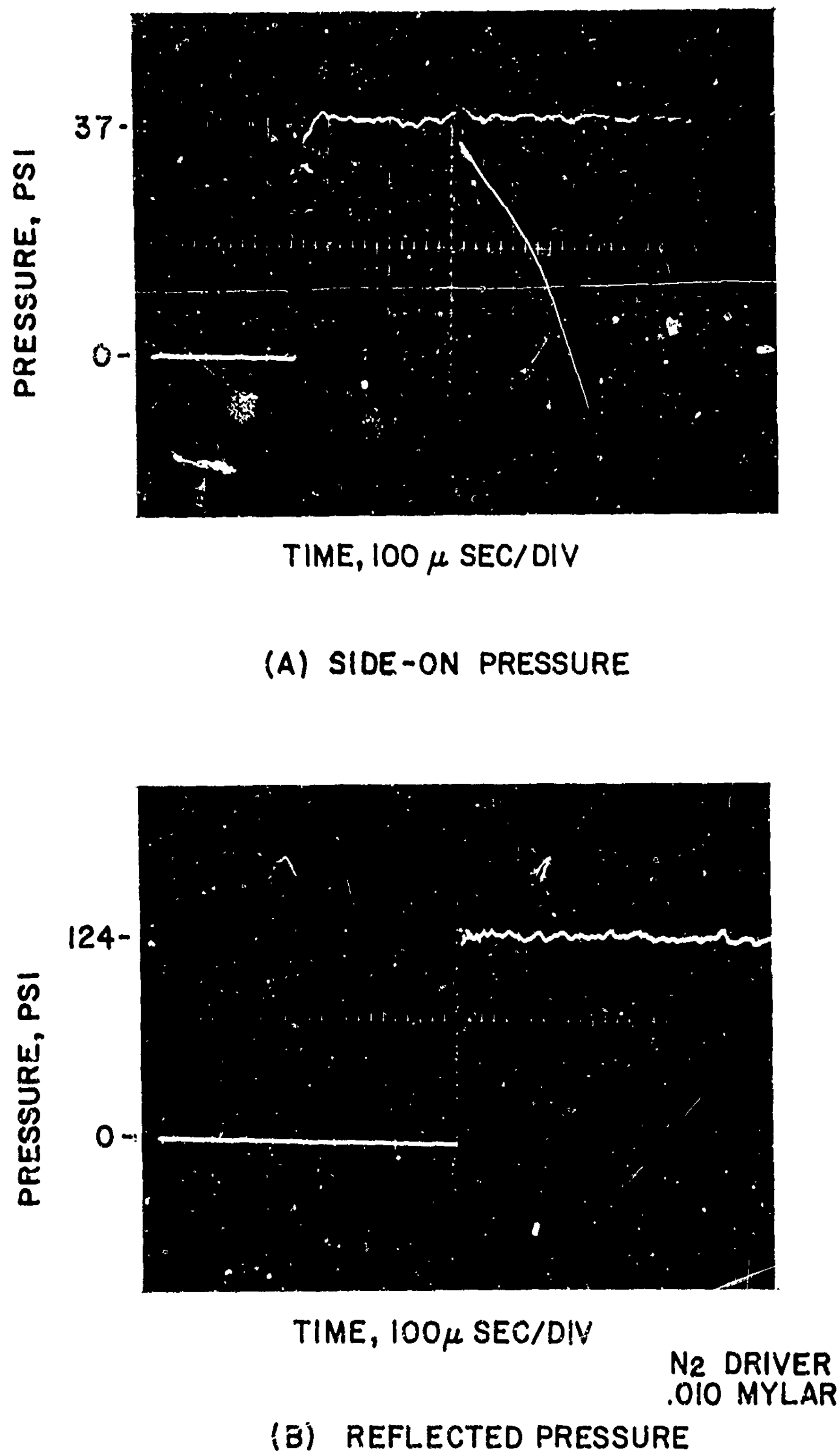
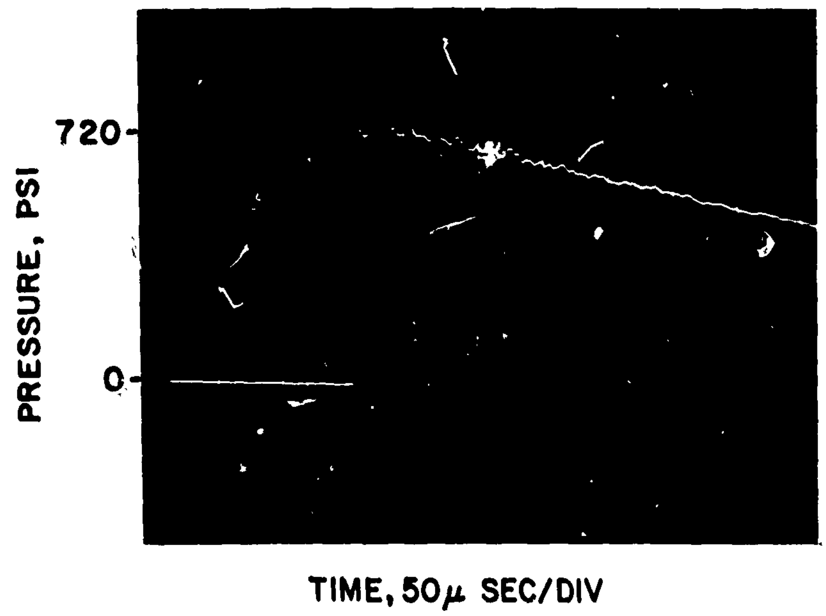
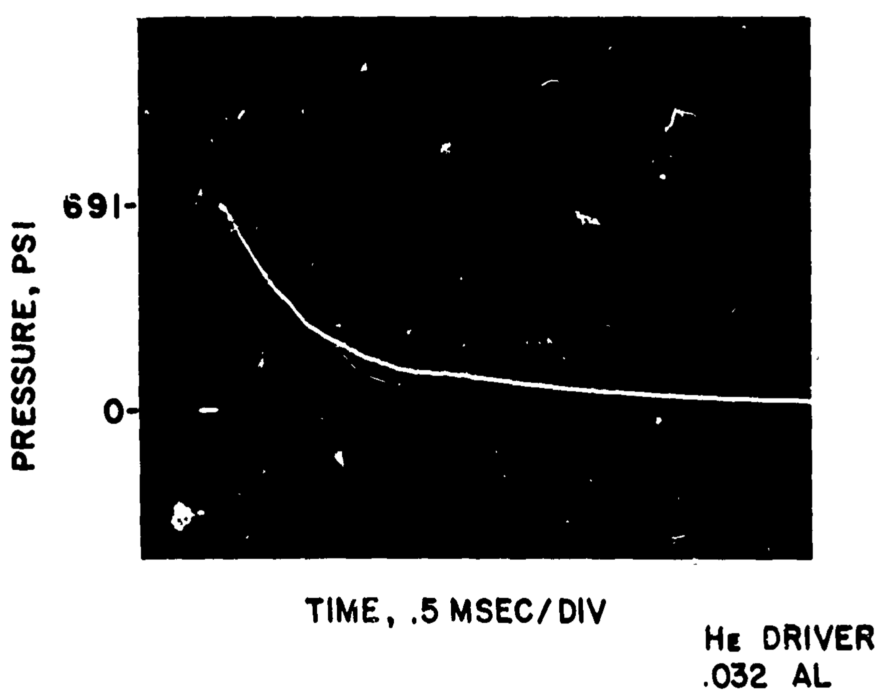


Figure 10. Typical pressure-time records from 2-inch shock tube



(C) REFLECTED PRESSURE



(D) REFLECTED PRESSURE

Figure 10. Typical pressure-time records from 2-inch shock tube (Continued)

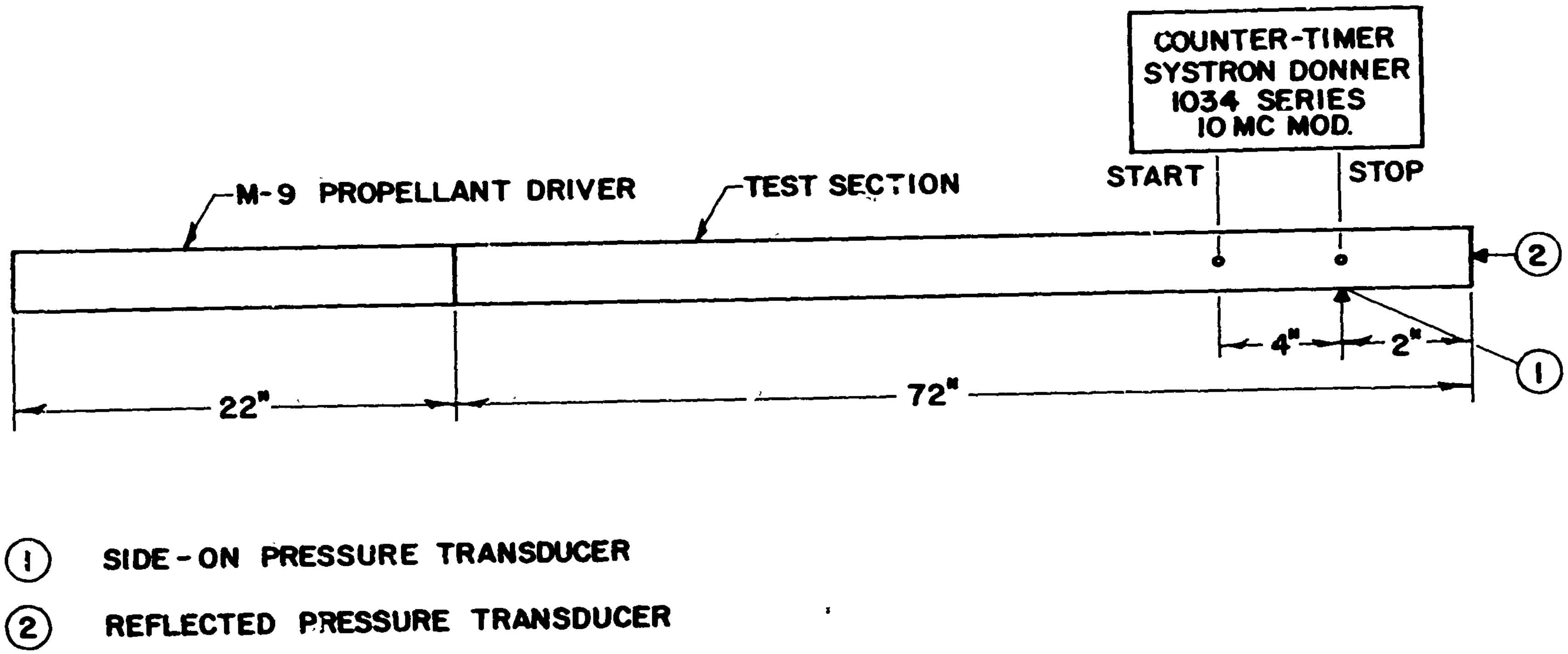


Figure 11. 2-Inch propellant driver shock tube

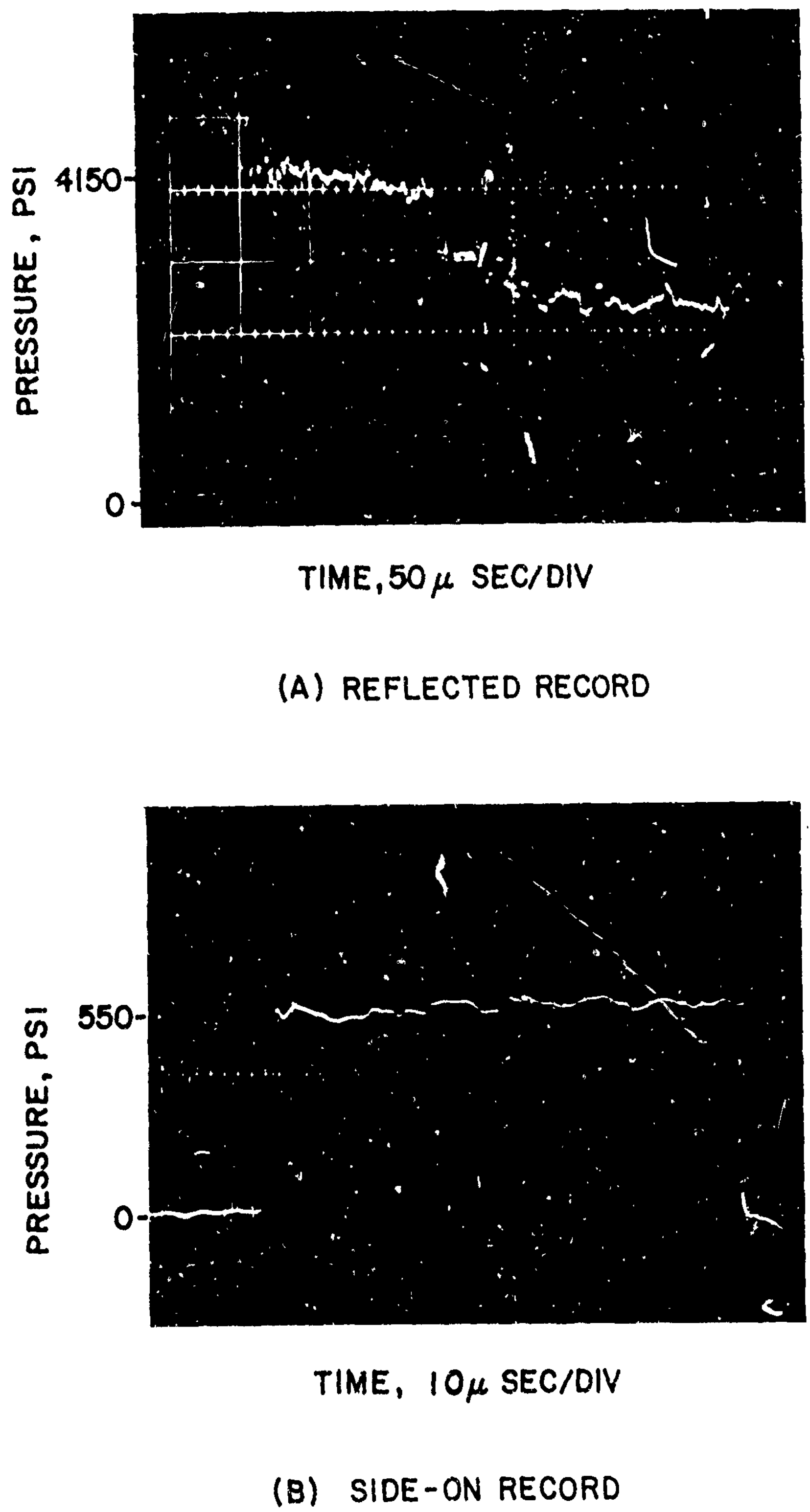


Figure 12. Pressure-time records from the propellant driver shock tube

IV. CALIBRATION BY DROP TEST

A third calibration system is presently in use which combines high pressures not obtainable in shock tubes with the simplicity of the air pulse calibrations.

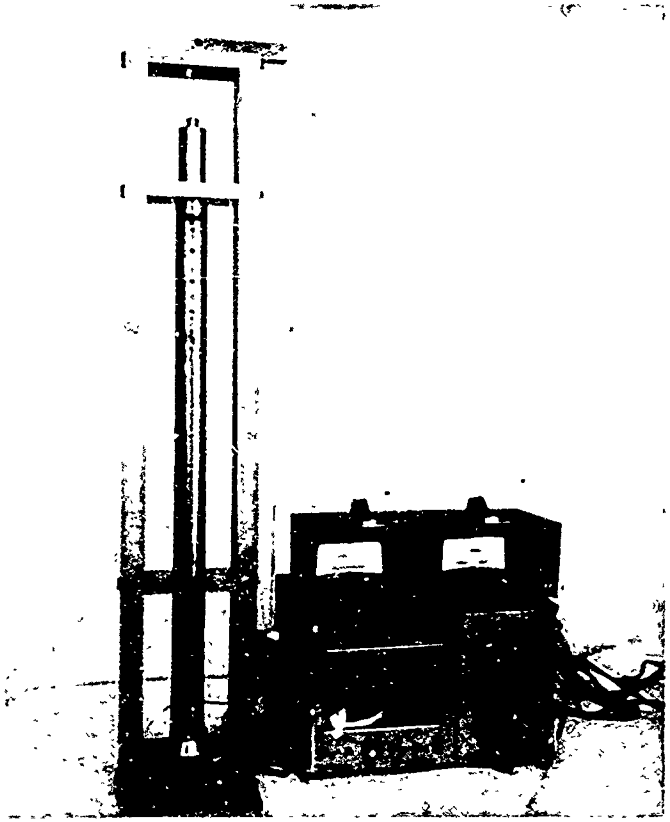
A. Drop Test Calibrator

Figures 13 and 14 show one of two drop test calibrators now in use. Both are designed from models in use at the Sandia Corporation Transducer Test Laboratory, Albuquerque, New Mexico. The smaller one, which is described here, is capable of providing pressures to about 25,000 psig; the larger model is designed for a maximum of 50,000 psig.

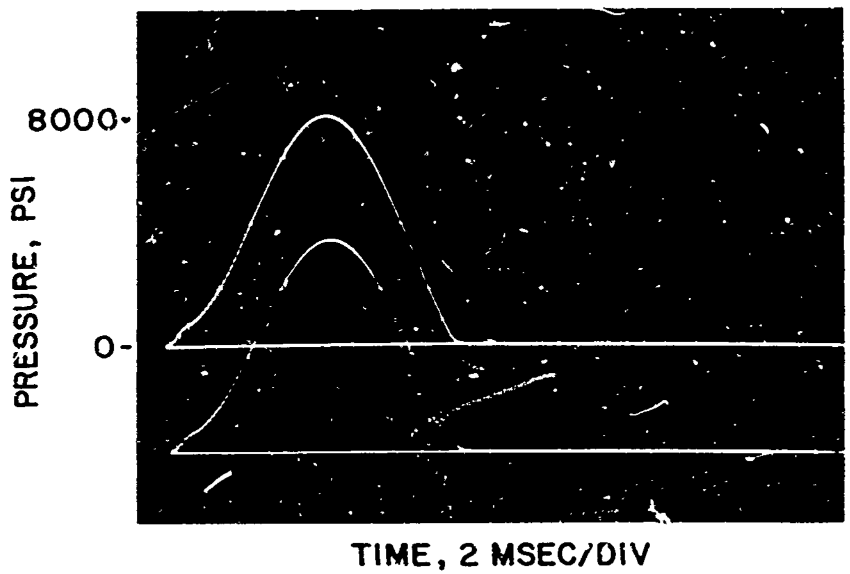
The drop tester consists of a rigid aluminum channel frame made of 1-3/8 x 3-inch stock bolted together to hold the vented brass guide tube of 1-3/4-inch OD. Steel or tungsten weights (4, 8, and 10 pounds) are dropped down the 4-foot long guide tube onto a 5/16-inch diameter piston. This piston is coupled by a thin silicone oil in the calibrator head, to the test and reference transducers. The cross-section view in Figure 14 shows additional details of the piston and calibrator head. A small rubber pad is used on top of the piston to damp unwanted oscillations on the traces. The interior calibrator head volume is kept small in order to couple most efficiently the force to the transducers.

An accurately calibrated and very linear tourmaline hydraulic transducer is used as a reference to compare with the test transducer when a weight is dropped to give a calibration pulse. The reference transducer is further discussed in Section IV-B.

The second drop tester is similar in design with larger components used. The frame is made of larger 1-5/8 x 4-inch channel; the weights are 3 inches in diameter and weigh 15 and 30 pounds. The exterior dimensions of the calibrator head are larger, but the interior volume and piston size have been left the same as in the smaller calibrator head. The maximum drop height has been increased from 4 feet to 6 feet. The maximum pressure range, as stated, is about twice the maximum range of the smaller tester, 50,000 psig.



(A) DROP TEST CALIBRATOR AND READOUT SYSTEM



(B) CALIBRATION PULSES
UPPER TRACE - HYDRAULIC REFERENCE
LOWER TRACE - TEST GAGE

Figure 13. Drop test calibrator with oscillographs of calibration pulses

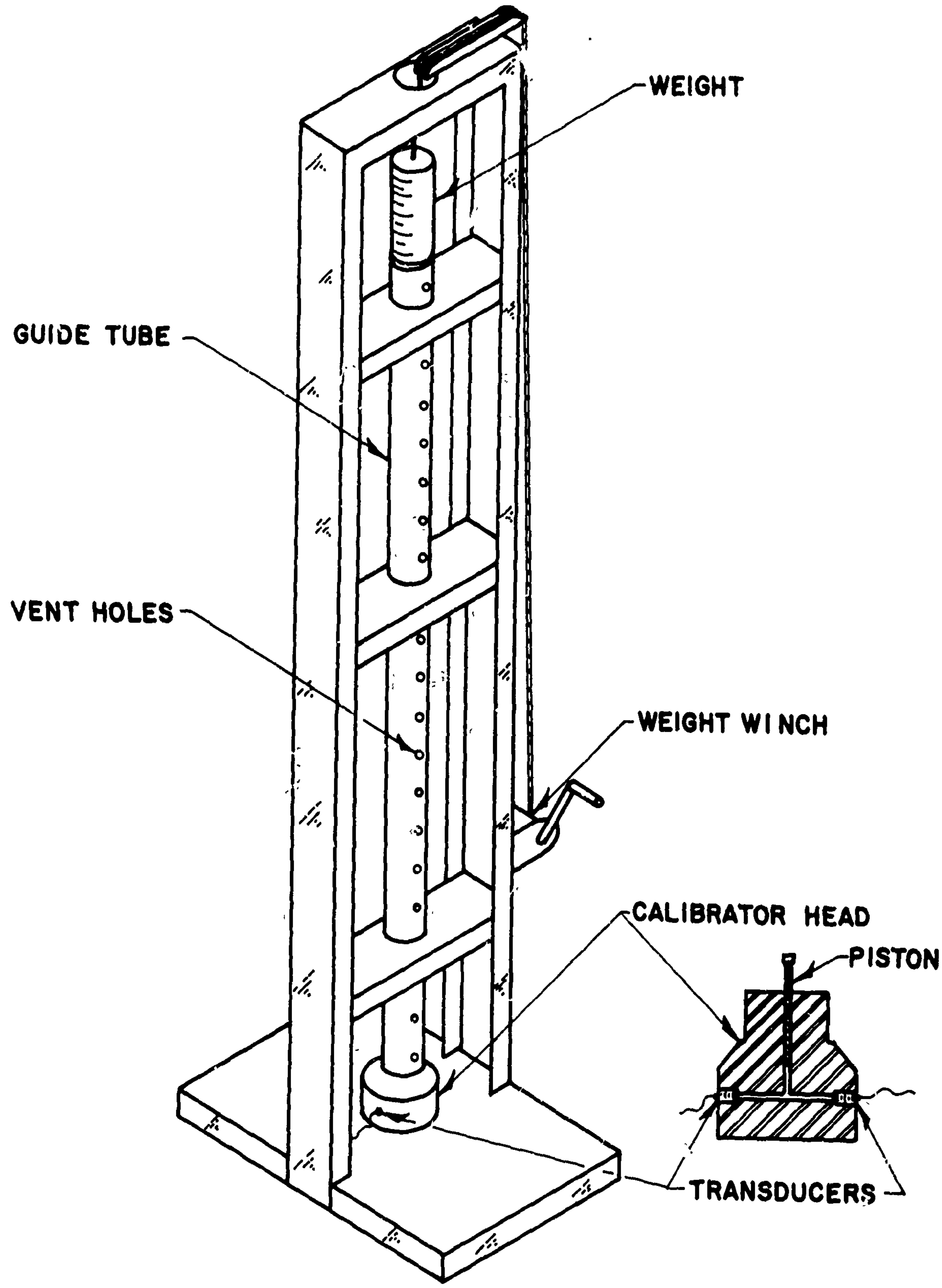


Figure 14. Drop test calibrator

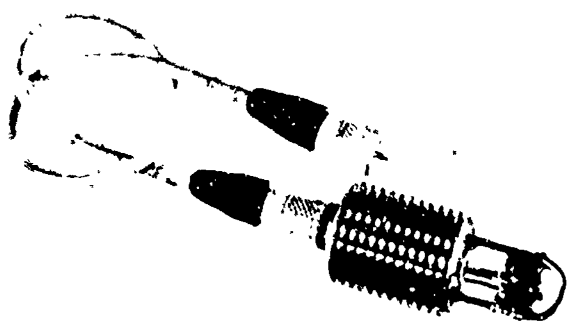
Both drop testers have oscilloscope and digital readout systems in use. Figure 13 shows the digital system which consists of two Kistler Peak Indicator-Charge Amplifiers Model 593, and two Trymetric Digital Voltmeters Model 400M. The charge and voltage reference is also used in the other calibration methods. The digital readout enables one to make fast, simple, and accurate (< 0.5 percent) calibration with the drop test calibrator.

B. Hydraulic Pressure Reference Transducer

Since commercial reference transducers of the strain gage-type do not seem to hold up under repeated dynamic pulsing, it was necessary to design and build a reference transducer suitable for the drop test calibrators.

A highly accurate tourmaline hydraulic pressure reference transducer was built using a single disc of tourmaline suspended free of edge effects or stress in a silicone oil. Since no covering diaphragm was used, a very linear transducer was obtained, with a full scale linearity of 0.4 percent. This is the limiting accuracy of our readout system, and the reference transducer may even surpass this accuracy. The useful pressure range is from 100 psig to 50,000 psig with a maximum frequency response of 100 KC.

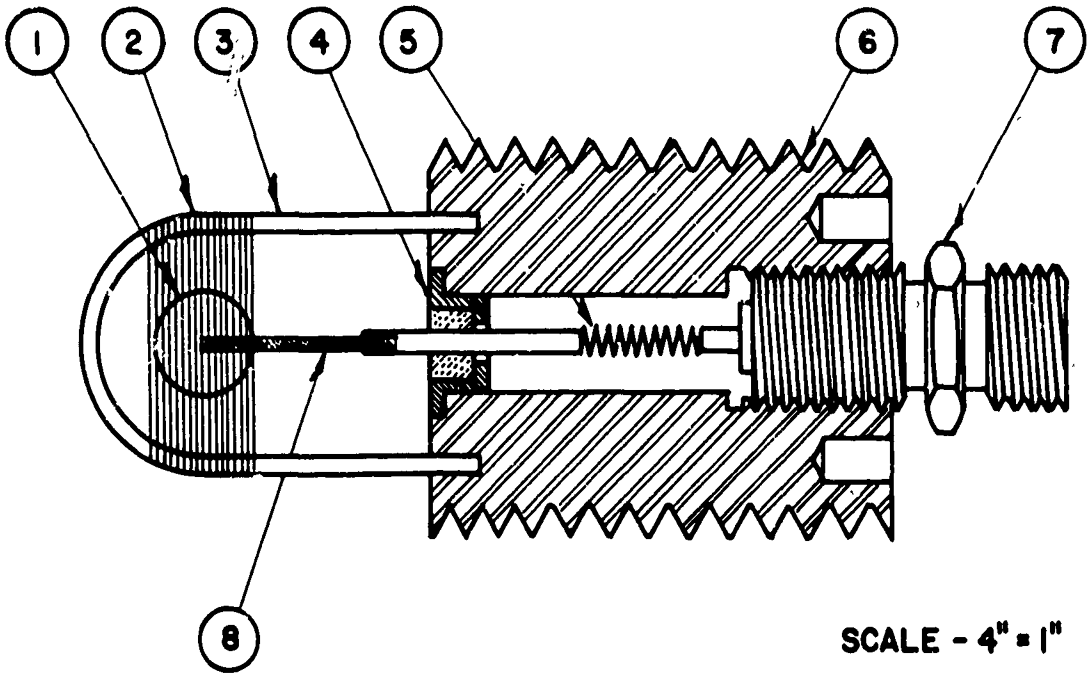
The transducer was constructed with a single gold plated tourmaline disc 0.150 inch in diameter by 0.005 inch in thickness. The disc was mounted to a supporting frame in a stress-free manner by using an epoxy filled non-conducting thread binding. The supporting frame was welded to the 1/2-inch - 20NF threaded stainless steel case. Electrical connections were made to the microdot chassis connector through a high pressure CEC Ceramicite seal Type 41-901-0001. Figures 15 and 16 are a photograph and a sketch of the reference transducer. The reference transducer has been accurately calibrated by a dead weight tester fitted with a quick release valve. Both the charge standard and the tester are traceable to the National Bureau of Standards.



(A) HYDRAULIC PRESSURE REFERENCE TRANSDUCER

(B) CHARGE AND VOLTAGE REFERENCE

Figure 15. Pressure and charge references for drop test calibrator



(1) TOURMALINE DISC .150 DIA. X.005 THICK GOLD PLATED

(2) EPOXY FILLED NON-CONDUCTING THREAD

(3) SUPPORT FRAME

(4) CERAMICITE SEAL

(5) CONTACT SPRING

(6) STAINLESS STEEL CASE

(7) MICRODOT CHASSIS CONNECTOR

(8) ELECTRICAL CONNECTION

Figure 16. Hydraulic pressure reference transducer

C. Charge and Voltage Reference Unit

All the calibration methods described above make use of a charge and voltage reference unit shown in Figure 15-B. The circuit schematic for the unit is shown in Figure 17. The charge range was chosen to correspond to the anticipated electrical output from tourmaline and lead metaniobate transducer elements of 0.10 to 0.25-inch diameter discs. A corresponding full scale voltage is available from $\pm$ 0.1 to $\pm$ 10 volts with 0.001 divisions of full scale voltage available by a ten-turn dial scale divider.

The reference unit serves three main purposes during the calibration tests. The first purpose is to furnish a charge reference pulse for comparison with the air pulse or shock pressure. This is needed for the calculation of charge output per unit applied pressure. Secondly, the trigger levels to the velocity system counters and digital voltmeters are accurately set to match the anticipated calibration pressures. Thirdly, the reference unit is used periodically to monitor the gain of the oscilloscope and charge amplifiers to detect any gain change during the tests. To insure reference unit accuracy, traceability is maintained to the National Bureau of Standards.

V. INFLUENCE OF TEMPERATURE UPON THE CALIBRATIONS

When exposed to a change in ambient temperature (indoors to outdoors), or a transient temperature (shock temperature), the sensing element of a transducer may experience a change in output.[10] This effect may either add to or subtract from the true pressure-time profile as recorded, and the error may be quite large.

A. Effect of Ambient Temperature

In order to evaluate the effect caused by ambient temperature changes, the pressure transducer is air pulse calibrated while it is in a temperature chamber. The chamber now in use is a Tenney Jr. Proportion Null 1300 Series with a temperature range from - 100 $^{\circ}$F to 350 $^{\circ}$F. This range covers most transducers used and caution has to be

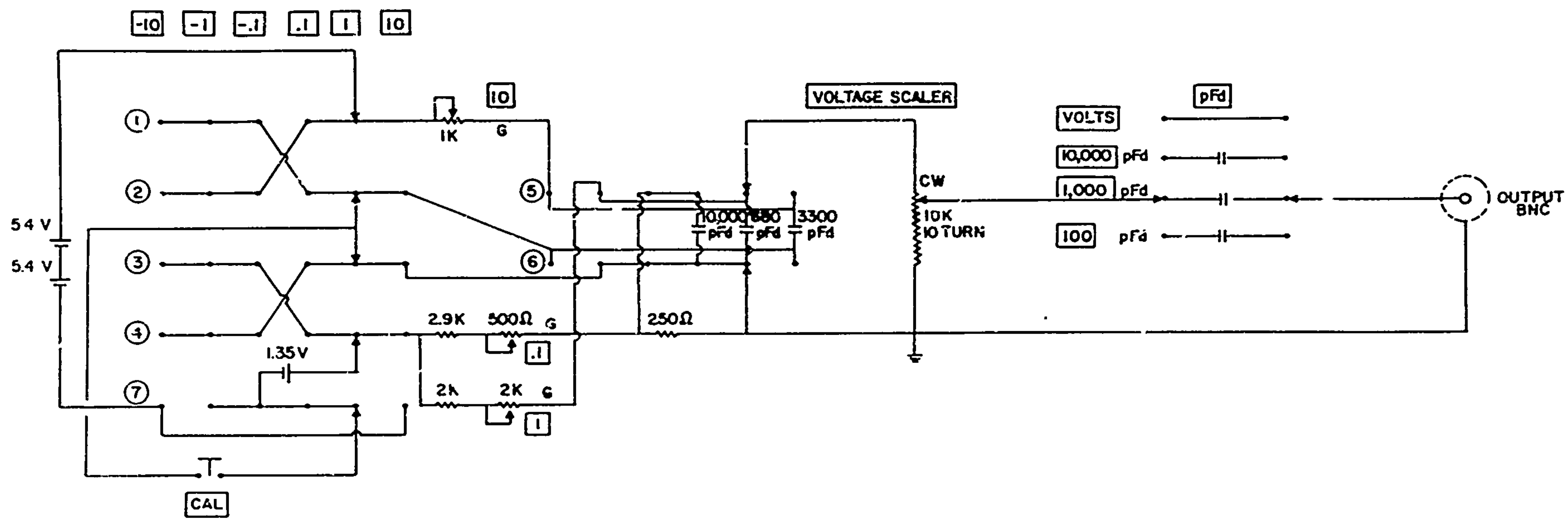


Figure 17. Circuit diagram for charge and voltage reference unit

observed not to exceed the manufacture's temperature specifications. The calibrations may be plotted as a function of temperature for outdoor use of the transducer.

B. Effect of Transient Temperature

In addition to changes in ambient temperature, there may be transient effects caused by transfer of heat to the transducer from the shock or blast wave when the transducer is exposed to the pressure. The pressure-time profile may be distorted by the transfer of heat to the transducer during this time.

Figure 18 shows a thermal pulser used to evaluate quantitatively the transducer's transient heat sensitivity with and without heat insulation. The thermal pulser exposes the transducer to a propane flame for a time determined by the length of an exposure slot and the drop height of the insulating shield. Figure 19 shows the effect of transient heat upon the output of a BRL-4 bar transducer without insulation, with one layer of insulation, and with two layers of Scotch No. 33 (3M), 0.007 inch thick tape. The output is shown as a variation of time when exposed to 90 msec of heat. Two layers of insulating tape are necessary to protect the transducer for about 75 msec. This conclusion holds only for a shock wave or blast wave with equal or less heat transfer than the propane flame which has a theoretical flame temperature of about 2100 °C.[11]

Usually only one layer of insulating tape is used with the BRL-4 transducer since it is used for measurements during a time range from microseconds to a few milliseconds. How the insulating tape affects the high frequency response is shown in Figure 20. The records shown are for a 700 psi reflected shock pressure upon BRL-4 bar transducer with no insulation, and compared with one, two, and three layers of Scotch No. 33 (3M), 0.007 thick black tape shielding the transducer. More than a single layer of tape seems to distort the early part of the record so that readings less than 5 microseconds might be suspect. If

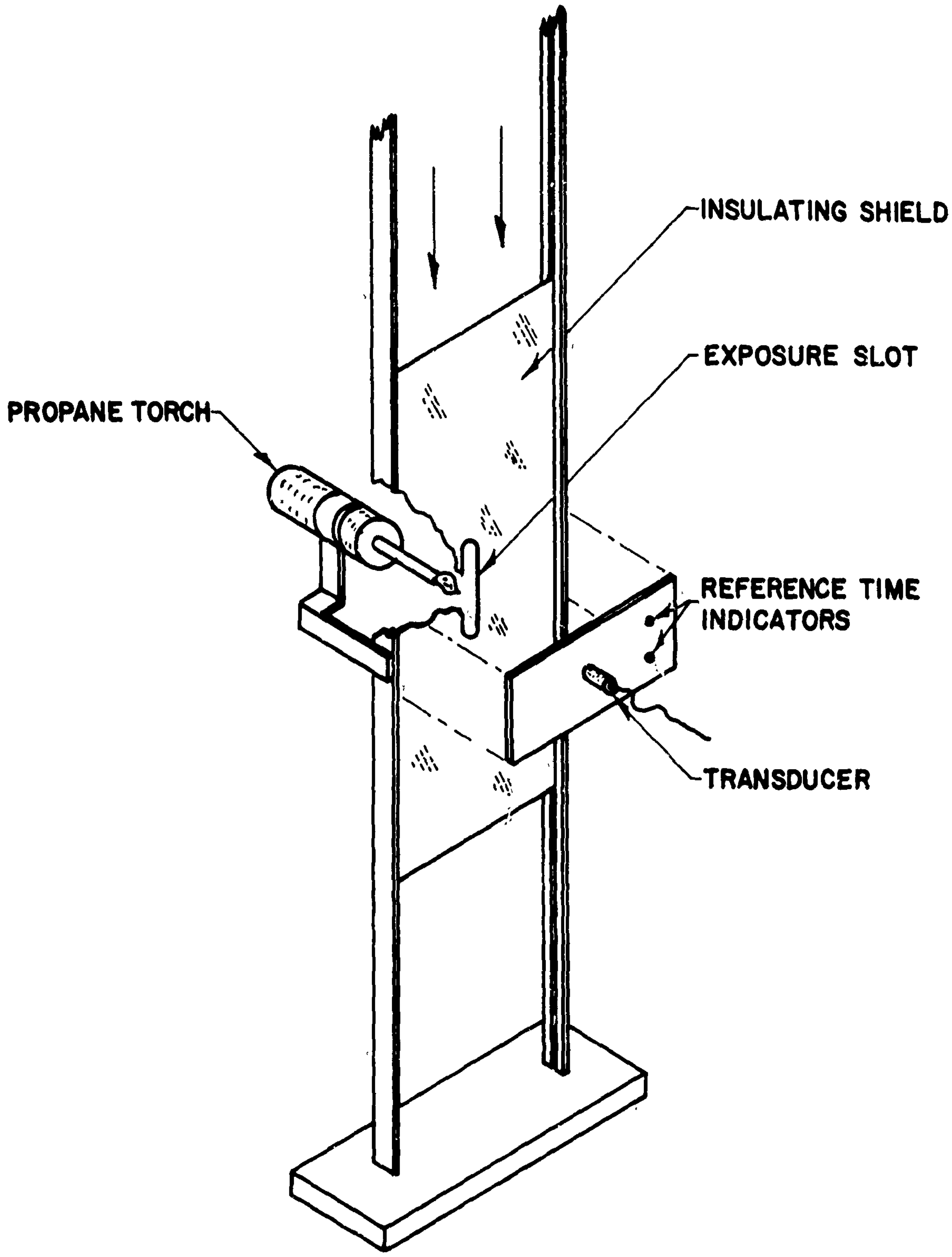


Figure 18. Sketch of thermal pulser

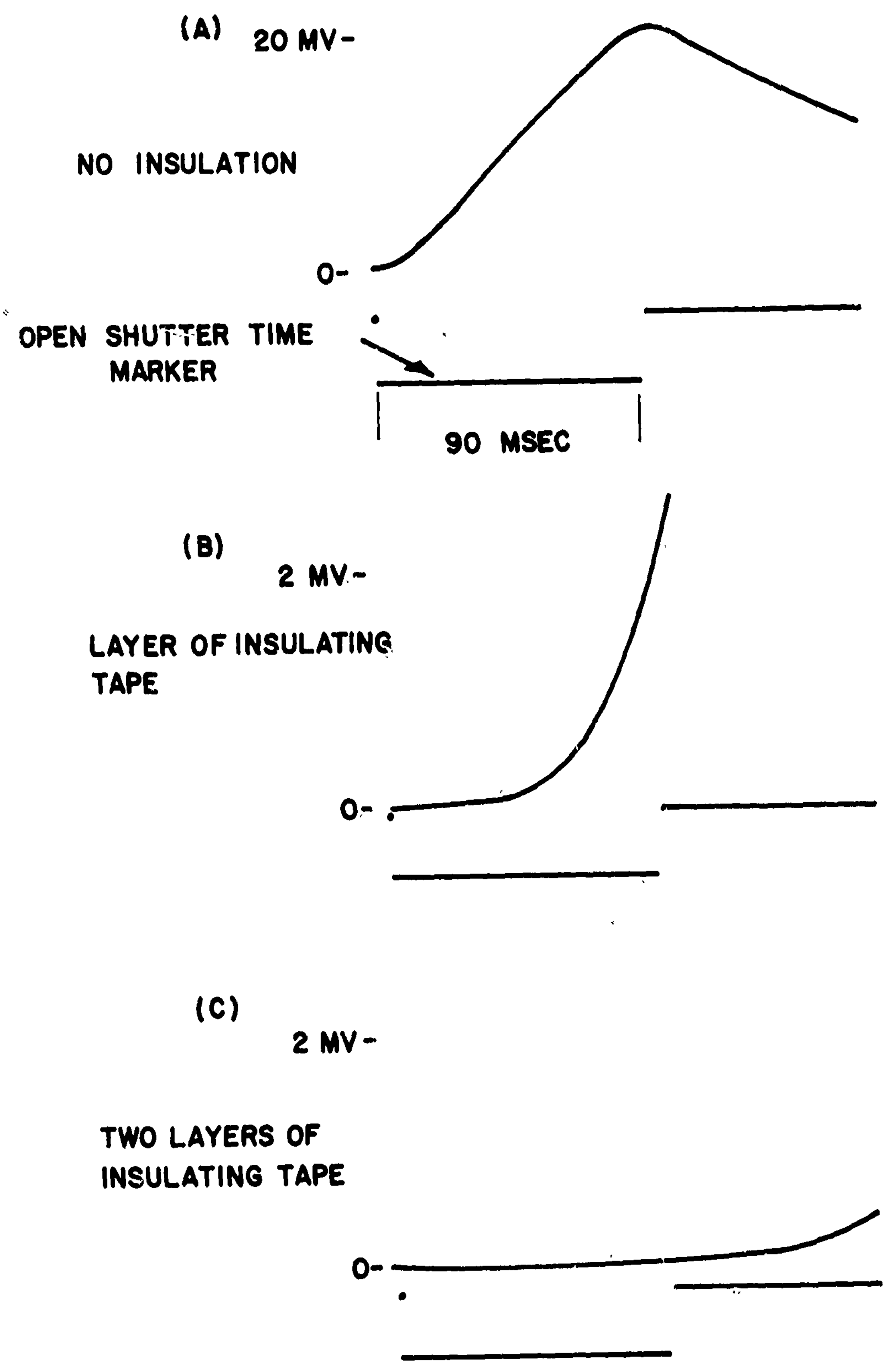


Figure 19. Traces showing effect of insulation on performance of piezo-gage

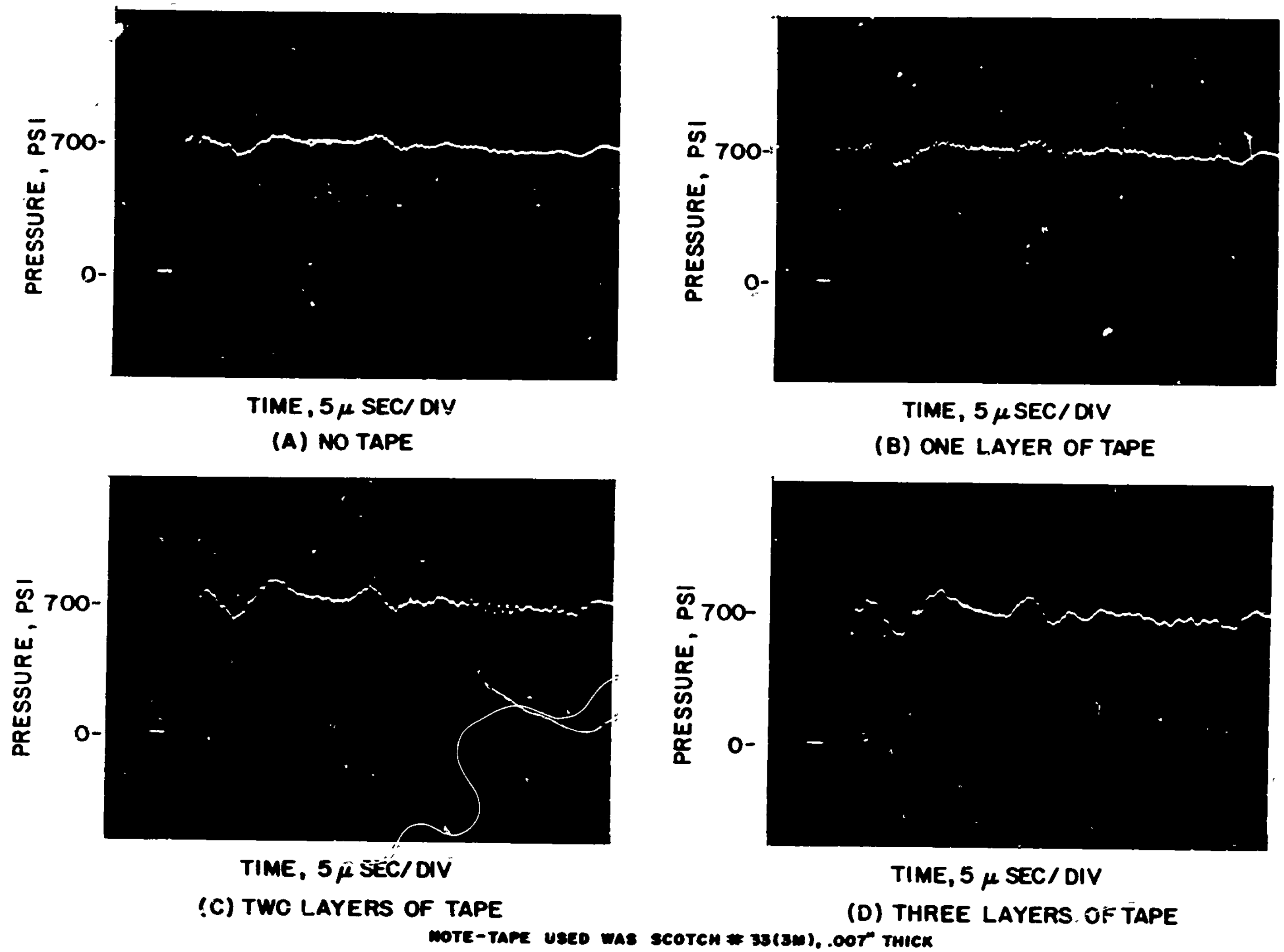


Figure 20. Effect of heat insulating tape on transducer response

much longer record times are desired (50 - 100 msec), two layers of tape might be used. As the pressure range is extended beyond the present test results, more error in the pressure-time profile from the transducer may be expected.

In summary, an accurate shock tube velocity system is used for transducer calibration; and three to five records read during the first few microseconds of shock front arrival are averaged. The calibrator constants for the transducer will be within a spread of ± 1.5 percent of the data from all the calibration methods. Transducers which do not fall within this range of accuracy are rejected.

VI. SUMMARY

Three methods of dynamic calibration transducers are in use at the BRL Shock Tube Facility. The test procedure is to first calibrate by means of an air pulse released from an air tank by a solenoid valve. The transducer output is observed by means of an oscilloscope to check the anticipated waveform. If the transducer appears to be functioning normally, several calibrations are made over the required pressure range with a digital voltmeter monitoring the output. This monitoring increases accuracy by eliminating human errors incurred during reading of electrical reference and pressure pulse records.

Second, the pressure range for calibration is extended above 2000 psi by the drop test calibrator. Any non-linearity of the transducer should appear during this part of the calibration tests. Again, the digital readout is used.

Last, the 2-inch calibration shock tube is used to test the transducer for high frequency response characteristics such as risetime, ringing, and duration of ringing. Any loss of frequency response caused by thermal insulation, by tape, or by other heat shields will be observed during this test when the transducer is in the reflected position in the shock tube.

To be put in service, a transducer should calibrate consistently within the $\pm$ 1.5 percent error spread for all the calibration methods.

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The author wishes to give credit to Mr. Rodney Abrahams for the design of the charge and voltage reference unit, and also the electrical transducer filter; to Mr. William Matthews for the planning of the Shock Tube Calibration Room; and to Mr. Benjamin Granath for the design of the tourmaline hydraulic reference transducers.

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APPENDIX

CHARACTERISTICS OF BRL SHOCK TUBE PIEZO-ELECTRIC BLAST GAGES

Table A-I. Characteristics of BRL Shock Tube Piezo-Electric Blast Gages

Type	Dia, in.	Length, in.	Stainless Steel Case Thread, ASME	Piezo-Electric Material	Natural Frequency, KC	Ringing Duration, μsec	Rise Time, μsec	Temp Range, °C	Accel Sensitivity, psi/g	Charge Output, pC/psi	Open Circuit Voltage, mV/psi	Pressure Range, psi	Linearity, % Full Scale
1	1/2	1-1/8	1/2-20	Tourmaline 0.150" dia	100	--	3.0	0-100	<0.005	0.200	20	50,000	±0.001
2	1/2	5/8	1/2-20	Lead Metaniobate 0.150" dia	250	50	0.8	0-40	0.0005	15-20	50	1-500	±2.5
3	1/2	5/8	1/2-20	Tourmaline 0.150" dia	450	20	0.4	20-50	--	0.150	15	1-1,000	±1.5
4	1/2	1-9/16	1/2-20	Tourmaline 0.125" dia	2,500	1	<0.2	0-50	0.005	0.130	13	10-10,000	±1.5
	3/4	3-1/4	3/4-16	Tourmaline 0.250" dia	1,500	3	0.2	0-50	--	0.450	2	10-2,000	±1.5

Note: The present gage numbering system replaces that of Table I, Reference 1.

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13. ABSTRACT
Dynamic pulse calibration methods and types of pulse calibrators currently in use at the Ballistic Research Laboratories (BRL) Shock Tube Facility are described. Records typical of the various calibration methods obtained from piezo-electric tourmaline transducers are shown. Results from the various calibration methods are found to be in agreement with each other within $\pm$ 1.5 percent.

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